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Effect of generator load on hybrid heat recovery system

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ABSTRACT

Heat recovery is the reutilization of lavished thermal energy. This paper proposes a hybrid heat recovery system that utilizes exhaust gases of a generator to heat water and produce electricity using thermoelectric generators. The system is composed of a concentric tank with a copper tube passing through it. At the inner surface of the tube, a layer of TEGs is located. The main purpose of the paper is to study the effect of changing the load of the generator on the water temperature and power generated. Knowing that 100 TEGs are utilized, results show that 47 °C hot water and 141 W are produced when load is 10 kW. It increases to 97 °C hot water and 1412 W when the generator load is 38 kW (14.12 W per TEG).

1. Introduction

Nowadays, worldwide face a major problem with energy. Lack of energy availability, limited sources of energy, high cost of energy and energy extraction and strict laws and emission regulations imposed by governments obliged to seek for efficient, economical, renewable and sustainable technologies for energy utilization and conversion.

Renewable energy has been set as one of the best solutions of those problems. However, such technologies are limited by time, place and availability. Solar, wind, biomass, geothermal, hydropower are the main types of renewable energy which are exposed to high studies and researches [1–11].

Energy recovery [12–19] appears also as a perfect solution for maximum energy utilization. It deals with the re-usage of energy dissipated to the environment. Such technology offers a new source of energy, decrease polluting emissions and increase the energy utilization efficiency.

Khaled et al. [17] did a theoretical and experimental study on a suggested heat recovery system. The system which is called multi-tubes tank allows exhaust gases to enter multi-tubes that passes through a water tank. Two cases were considered by which exhaust gases are allowed to enter the tubes or to flow beside the bottom side of the tank in order to study the effect of tubes on the amount of heat transferred to water. In addition to that, effect of changing the quantity of burned fuel is studied. Results show that during one hour water temperature rises 68 °C when the tubes are open and 38 °C when the tubes are closed. Scarce are the studies on hybrid heat recovery systems that utilizes exhaust gases to heat water and generate electricity. Jaber et al. [20] performed a mathematical thermal study on hybrid heat recovery system that utilizes exhaust gases of chimney to heat water and generate electricity using thermoelectric generators. The effect of changing the location of TEGs on the suggested heat recovery system is examined. The TEGs are located in the inner or outer walls of the tube or the tank (cases 2–5) and in all walls in case 6. Results conducted shows that as the

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TEGs are located nearer to the exhaust gases the power generated increases, increasing the energy conversion efficiency of TEGs. In addition to that water can be heated up to 76 °C and generate about 34.8 W of electricity when the TEGs are located at the inner side of the tube. Moreover, Water temperature increases when the TEG location become more far from exhaust gases. Whereas when the TEGs are placed on all surfaces (case 6) water temperature rises to 81 °C and about 52 W electric power is generated. The paper also includes an economic and environmental study which shows that the location of TEGs does not affect the amount of CO_2 gas reduced (6 t/year) and such system with case 5 configuration requires 1 year and 8 months to payback its cost. [13] studied the effect of exhaust gases temperature on the performance of hybrid heat recovery system. Exhaust gases enter a heat recovery heat exchanger that utilizes thermal energy captured by gases to heat water and generate electricity. A thermal modeling of the system is presented. The main outcomes reached show that as the exhaust gases temperature increase, the heat rate and the temperature at each layer of the system increase and power generated by TEGs increase. It shows that when exhaust gases temperature is doubled, power generated increased five times.

This paper deals with a new proposed hybrid heat recovery system that utilizes exhaust gases to heat water and generate electricity. The study is performed on exhaust gases of a diesel engine. The effect of changing the load of the generator on the water temperature and power produced are studied.

The hybrid heat recovery system (HHRS) is demonstrated in Section 2. Section 3 shows a thermal modeling of the system. Several generators with different loads are studied in Section 4 that provides results and discussion of the associated results. Finally, a summarizing conclusion is drawn in Section 5.

2. Hybrid heat recovery system

The high amount of dissipated thermal energy obliged engineers to seek for ways to benefit from this energy. System with single or multiple stages of heat recovery was proposed and studied. This paper proposes a new hybrid heat recovery system that deals with the cogeneration of domestic hot water and production of electricity using thermoelectric generators (TEGs). Fig. 1 shows a schematic of the hybrid system where exhaust gases enter to a concentric tube tank. At the inner wall of the copper tube, a layer of TEGs is placed for the electricity production purpose. Water surrounds the copper tube which gains its heat from exhaust gases to the TEGs to the water.

Thermoelectric generators [21–25] are passive devices that convert thermal energy to electrical energy directly [26]. The TEGs are placed to gain heat from exhaust gases to water. When a temperature difference is applied at the sides of the TEG, an electric power is produced. Fig. 2 presents a schematic of a TEG which consists of P and N-type semiconductors. The main advantages of thermoelectric generators are summarized by their simplicity, minimal maintenance requirement and reliability. However, they exhibit low energy conversion efficiency and high cost [26].

3. Thermal analysis

To analyze the effect of the generator load on the water temperature and power produced by TEGs a thermal modeling is carried. The system is represented by a thermal resistance model. Some assumptions are utilized to simplify the calculations. The heat flow is assumed to be one dimensional flow at steady state. The exhaust gases and air temperature are set to be constant.

Fig. 3 presents the resistance thermal modeling of the system. It shows a seven thermal resistance model. Starting from hot exhaust gases, heat transfer occurs from gases to the hot side of the TEG by convection. Then, heat flows through TEG to the tube's wall by conduction. At the outer wall of the tube, heat transfer occurs toward water via convection in which water delivers heat to the inner wall of the tank via convection. A conduction heat transfer occurs at the tank's wall. Finally, heat is dissipated to ambient air via convection.

The heat rate occurs from the exhaust gases to the ambient air and expressed by the following equation.

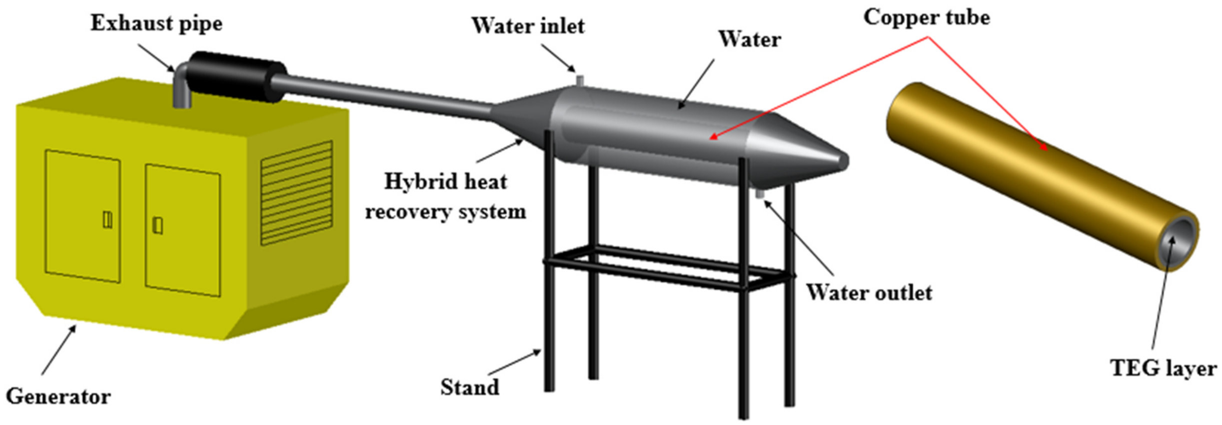

Fig. 1. Hybrid heat recovery system coupled to exhaust of an electric generator.

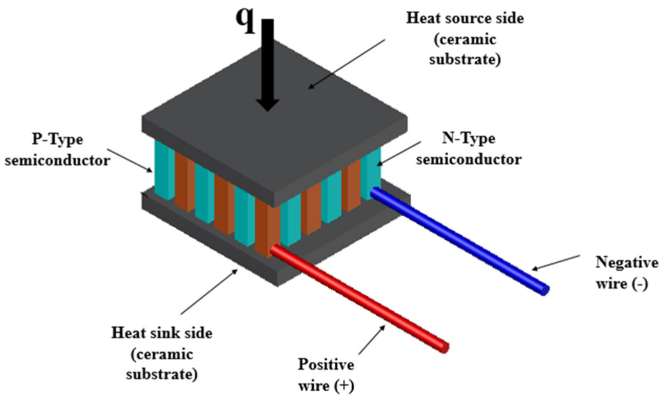

Fig. 2. Thermoelectric generator.

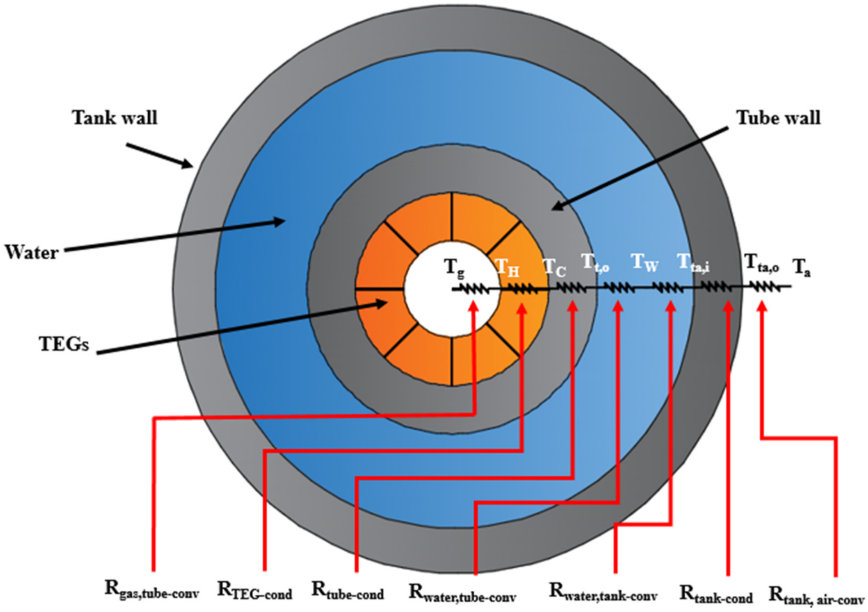

Fig. 3. Resistance thermal model of the hybrid heat recovery system.

$$q = \frac{\Delta T}{R_{total}} = \frac{T_g - T_a}{R_{total}} \tag{1}$$

where T_g, T_a are the exhaust gases and air temperature respectively. R_{total} is the summation of the seven resistances and represented by:

$$R_{total} = \sum_{n=1}^{7} R_n = \begin{Bmatrix} R_{gas,tube-conv} + R_{TEG-cond} + R_{tube-cond} + R_{water,tube-conv} \\ + R_{water,\ \tan k-conv} + R_{\tan k-cond} + R_{\tan k,air-conv} \end{Bmatrix} \tag{2}$$

where $R_{gas,tube-conv}$, $R_{water,tube-conv}$, $R_{water,\ \tan k-conv}$ and $R_{\tan k,air-conv}$ are the four convection thermal resistances between exhaust gases and tube, tube and water, water and tank, tank and air respectively. $R_{TEG-cond}$, $R_{tube-cond}$ and $R_{\tan k-cond}$ are the three conduction thermal resistances of thermoelectric generators, tube and tank respectively.

Table 1 below shows the equation of each thermal resistance, knowing that h_g, h_w and h_a are the convection heat coefficient of exhaust gases, water and air respectively, k_{TEG}, k_t and k_{ta} are the conduction heat transfer coefficient for TEG, tube and tank. $r_{t,i}$, $r_{t,o}$, $r_{ta,i}$ and $r_{ta,o}$ are the inner and outer radii of the tube and tank respectively.

After estimating the total resistance, the heat rate is evaluated using Eq. (1). By calculating the heat rate, temperature at each section on the system is estimated by the following equation.

$$T_{\sec} = T_{pre-\sec} - q.\quad R_{\sec} \tag{3}$$

where $T_{\sec}$ and $T_{pre-\sec}$ are the temperature at the section and previous section respectively. $R_{\sec}$ is the thermal resistance of the section.

Table 1
Thermal resistance equations.

Heat transfer type	General form	Thermal resistance equation			
Convection	$\frac{1}{h.\ A}$	$R_{gas,tube-conv}$ $\frac{1}{h_g\ (2\pi\ (r_{t,i}-t)\ L)}$	$R_{water,tube-conv}$ $\frac{1}{h_w\ (2\pi\ r_{t,o}\ L)}$	$R_{water,\tan k-conv}$ $\frac{1}{h_w\ (2\pi\ r_{ta,i}\ L)}$	$R_{\tan k,air-conv}$ $\frac{1}{h_a\ (2\pi\ r_{ta,o}\ L)}$
Conduction	$\frac{\ln\left[\frac{r_o}{r_i}\right]}{2\ \pi.\ K.\ L}$	$R_{TEG-cond}$ $\frac{\ln\left[\frac{r_{t,i}}{r_{t,i}-t}\right]}{2\pi\ k_{TEG}\ L}$	$R_{tube-cond}$ $\frac{\ln\left[\frac{r_{t,o}}{r_{t,i}}\right]}{2\pi\ k_t\ L}$	$R_{\tan k-cond}$ $\frac{\ln\left[\frac{r_{ta,o}}{r_{ta,i}}\right]}{2\pi\ k_{ta}\ L}$	

Then the power of one TEG $P_{generated}^{TEG}$ is calculated as follows:

$$P_{generated}^{TEG} = (P/\Delta T^2)_{ref}\ .\ \Delta T_{TEG}{}^2 \tag{4}$$

where ΔT_{TEG} is the temperature difference at the thermoelectric generator.

The total power produced by thermoelectric generators $P_{generated}^{total}$ is the summation of all power produced by TEGs, or calculated by the following equation.

$$P_{generated}^{total} = P_{generated}^{TEG}\ .\ N_{TEG} \tag{5}$$

where N_{TEG} is the number of thermoelectric generators attached to the inner wall of the tube.

4. Case study and results

To perform the study, a "13 B Toyota" 4 cylinder water cooled diesel engine is utilized [27]. The engine is of 102 mm bore and 105 mm stroke with a 217 N torque at 2200 rpm. The temperature of exhaust gases is measured at nine different loads, which are summarized in Table 2. As the load increases, exhaust gases temperature increases, from 180 °C at 7.5 kW load to 640 °C at 38 kW load.

The hybrid heat recovery system is composed of 100 TEG and 187 l water tank. The main parameters needed to apply Eqs. (1)–(5) are recapitulated in the Table 3.

By applying Eqs. (1), (2), (3), (4), (5) and using Table 2 and Table 3, the following results are conducted.

Fig. 4 shows the evolution of the different temperatures according to the generator load. As the load of the generator increases, temperature at each section increases. It shows high change in temperature at the TEGs when load is changed, T_H reached more than 500° at the maximum generator load (38 kW), that leads to a high increase in power produced by TEGs. Water temperature T_w increase from 43 to 97 °C when the load is increased from 7.5 to 38 kW. Augmentations of temperatures are more or less proportional to the increase of the generator load until about 30 kW, and beyond this value the temperature increase is slightly accelerated, indicating a decrease in the efficiency of the generator and a better recuperation of energy from the recovery heat system.

Fig. 5 shows water temperature and total power produced according to the generator load. As the load increases, water temperature and total power produced increase. When the generator load is 10 kW water temperature is 47 °C and power produced by TEGs is 141 W. While, when the generator load is increased to 38 kW water temperature reached 97 °C and TEGs generated 1412 W, i.e. 14.12 W per TEG. As Eq. (4) mentioned the power produced by TEGs is proportional to the square of the temperature difference, this leads to the high increase in power generated since the power generated is multiplied by a 10 factor when the load is increased from 10 to 38 kW.

As a brief summary of the results conducted, as the generator load increase, power generated and water temperature increases. In addition to that the temperature at each layer of the system has increased with the increase in the load. The conducted results perfectly match with the results associated by [13]. It should be noted that as the generator load increase, the quality and quantity of exhaust gases changes. In other words, mass flow rate and temperature of exhaust gases varies with the change of the load leading to the increase in heat transfer rate to water and TEGs which led to increase water temperature and power generated.

Table 2
Electric generator specification [27].

Load (kW)	Load (kVA)	Exhaust gas temperature (°C)
7.5	10	180
10	12	220
15	18	270
20	25	325
25	30	385
30	37	460
35	43	555
37.5	47	620
38	50	640

Table 3
Main parameter of the HHRS.

Item	Value	Unit
Inner tube radius	0.049	m
Outer tube radius	0.05	m
Inner tank radius	0.249	m
Outer tank radius	0.25	m
Length of the tank	1	m
Conduction heat transfer coefficient of TEG	0.25	W/m K
Conduction heat transfer coefficient of the tube (Copper)	401	W/m K
Conduction heat transfer coefficient of the tank (Iron)	80	W/m K
Convection heat transfer coefficient of exhaust gases	64	W/m^2 K
Convection heat transfer coefficient of water	25	W/m^2 K
Convection heat transfer coefficient of air	80	W/m^2 K
Thickness of TEG	0.005	m
Area of TEG	0.0031	m^2
Ambient air temperature	25	°C
$P/\Delta T^2$	0.00065	W/K^2

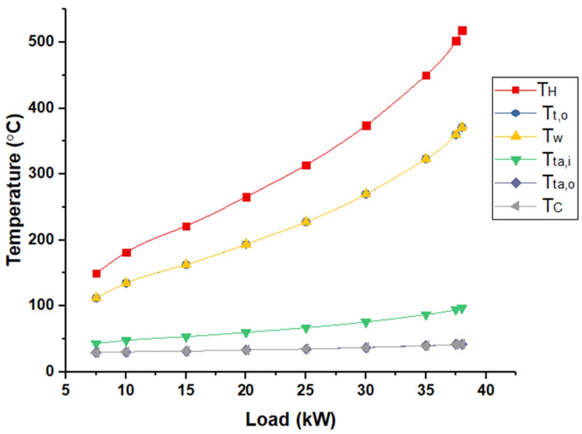

Fig. 4. Temperature at each section with the change of the load.

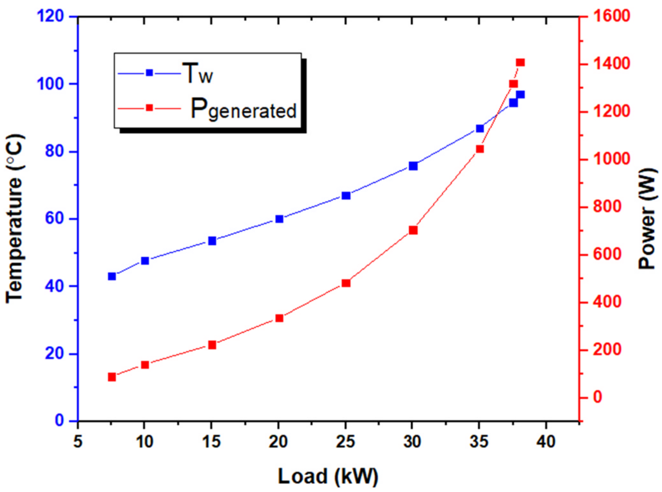

Fig. 5. Water temperature and total power produced by TEGs as function of load.

5. Conclusion

Since domestic hot water is the main electric consumption post in homes, various studies were performed to utilize new sources of energy to feed home with domestic hot water without the utilization of electric power. Heat recovery from exhaust gases provides a source of energy that can be easily utilized to produce hot water. This paper go beyond heating water, it deals with heating water and generating electricity by a proposed hybrid heat recovery system. The recovery system is explained showing that electric power is generated using thermoelectric generators. The exhaust gases of diesel engine are set as the wasted heat source. Exhaust gases enter a concentric tube water tank equipped with layer of TEGs. A thermal modeling of the system is carried. The effect of changing the load of the generator on water temperature and electric power produced is mainly studied throughout this paper. Results show that as the load increases the water temperature and power produced increases. Such system is capable to produce 47 °C hot water and 141 W electric power for a 10 kW load generator with 100 TEGs utilized. It increases to 97 °C hot water and 1412 W electric power when 38 kW load generator is utilized with same number of TEGs.

Conflict of interest

None.

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